Stefan Unnasch (Stefan Unnasch)

Thank you for your efforts to promote SAF in the State of Washington. Facilitating permits and favorable tax treatment go a long way towards accelerating the commercialization of synthetic aviation fuels. Our analysis has shown that SAF produced via the Fischer Tropsch process has an inherently low carbon intensity and that the feedstock- RFS compliant thinnings and slash have a low ILUC risk. Please refer to our attached studies.

Residual Biomass to Biofuels

Carbon Balance, Alternative Fate, & Verification

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Introduction

Biomass Energy

Biomass resources offer a promising pathway to displace petroleum fuels ad reduce greenhouse gas (GHG) emissions. The United States has a vast and diverse supply of biomass resources, including agricultural residues, forest residues, and municipal solid waste. These resources can be converted into biofuels, such as ethanol and biodiesel, or used to generate electricity and heat. The Billion Ton Study (Langholtz, 2016) conducted by the U.S. Department of Energy (DOE) assessed the potential availability of biomass for energy purposes in the United States, and concluded that it is feasible to produce one billion dry tons of biomass annually by 2030 without compromising food, feed, and fiber production.

The Federal Renewable Fuel Standard (RFS) requires the production of cellulosic biofuels including feedstocks from forest and agricultural residues (EPA, 2023). The RFS sets annual volume requirements for cellulosic biofuels, which helps to promote the development and use of biomass energy technologies. State policies, such as California's Low Carbon Fuel Standard (LCFS), will also play a role in advancing biomass energy technologies. However, guidance and crediting for biomass-to-fuel pathways is lacking in state LCFS programs, which is hindering advancements in this area.

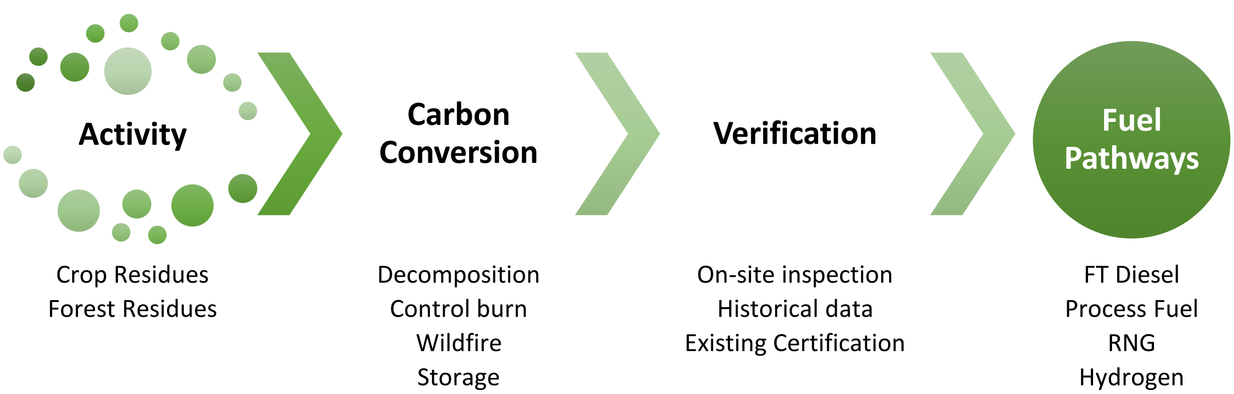

Figure 1. A path forward for waste biomass to biofuel pathways illustrates the key considerations for biomass residues to fuel pathways. Crop and forest residues result in variety of baseline carbon conversion processes, such as decomposition, control burns, wildfires, and storage. Baseline historical data or existing certification must be verified to comply with GHG programs. Biomass residues can be converted to variety of finished biofuels, such as FT diesel and jet, renewable natural gas, and hydrogen (Redmond & S. Unnasch, 2023).

The GHG impacts of biomass feedstocks depend on the type of feedstock and its alternative fate (Figure 1). This report summarizes the GHG emissions associated with the use of biomass feedstocks used to generate fuels and proposes a path forward for biomass residue to biofuel pathways within a range of regulatory emissions reduction frameworks. The goals of this paper are to:

- Develop a framework for biogenic carbon accounting
- Define a scope of emissions, monitoring, and verification requirements
- Establish biomass sustainability verification guidelines

Sources of Biomass

The characteristics of biomass are an important aspect of a life cycle GHG assessment. Collection and processing inputs as well as the avoided fate of biomass affect the GHG footprint of biofuel pathways. Five categories of biomass residues are shown in Figure 2. Each category exhibits unique characteristics and alternative fates that significantly impact carbon exchanges throughout the biomass life cycle. Understanding these implications is essential for accurately representing the GHG emissions reductions associated with biofuel production and utilization. The GHG impact of each feedstock is contingent on its alternative fate. While some biomass categories may present challenges in defining their potential alternative fates, this paper primarily focuses on forest residues which have well-defined criteria for collection under the RFS.

Energy Crops	Crop Residues	Forest Residues	Urban Landscaping Residues	C&D Waste
Crops that are grown specifically for their energy content. ○Switchgrass ○ Miscanthus ○ Willow	Residues from agricultural crops. ○Corn stover ○ Wheat straw ○ Rice straw	Waste materials from forestry operations. ○Thinnings ○ Slash ○Stumps	Waste materials from urban landscapes. ○ Grass clippings ○ Yard waste	Waste materials from construction and demolition activities.

Figure 2. Biomass Categories and Examples.

Biogenic Carbon Balance

Every year, over 100 billion metric tons of carbon dioxide (CO_2) are exchanged between the atmosphere and terrestrial biomass[1]. This exchange occurs through photosynthesis, respiration, decomposition, and combustion. Biomass residue feedstocks, such as agricultural waste and forest residues, would normally decompose or combust, releasing CO_2 into the atmosphere. However, converting biomass residue into biofuels can reduce overall amount of CO_2 emissions to the atmosphere by replacing conventional transportation fuels as shown in Figure 3).

The carbon embodied in biomass is a result of photosynthesis and is often referred to as biogenic carbon. Biogenic carbon is absorbed by plants during photosynthesis and later released during decay or combustion. However, this approach depends on the timeframe for the carbon cycle. The timing of the growth and removal of biomass affects its net GHG emissions. The case of sustainably harvested residues represents a relatively simple variant with the broader category of biomass feedstocks. Biomass residues are not produced for the purpose of biofuel production,

[1] IPCC, 2021: Chapter 5. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate.

and thus the carbon sequestered during uptake would have occurred regardless of whether or not the biofuel system existed. Therefore, in the case of waste-based fuels the net GHG emissions depends on the alternative fate of the material.

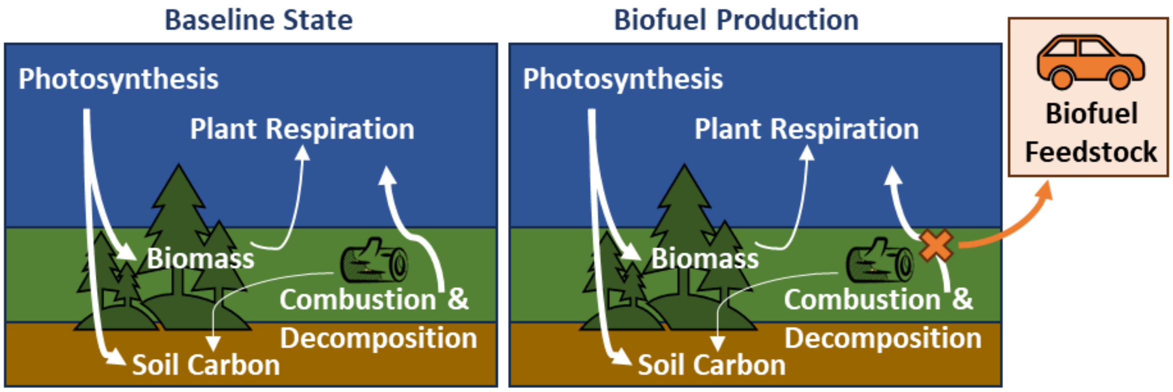

Figure 3. The Biogenic Carbon Cycle. Arrows are not drawn to scale.

System Boundaries

Assessing the net GHG emissions of a biomass derived biofuel involves a comprehensive approach known as Life Cycle Assessment (LCA). LCA evaluates the environmental impact of a product or process across its entire life cycle, from the extraction of raw materials to its eventual disposal. Assessing the carbon intensity (CI) of biofuels begins by establishing baseline data and cataloging the energy and materials consumption of all involved processes, including carbon capture, transportation, storage, and monitoring. Life cycle GHG emissions correspond the net emissions released into the environment amortized over the amount of fuel produced.

In the case of biomass residuals, the system boundary includes:

- Biomass production and collection, including direct and indirect land use change
- Transportation of biomass to the facility
- Biomass preparation, including biomass chipping or grinding
- Biofuel production
- CO_2 sequestration and storage (CCS)
- Fuel Combustion

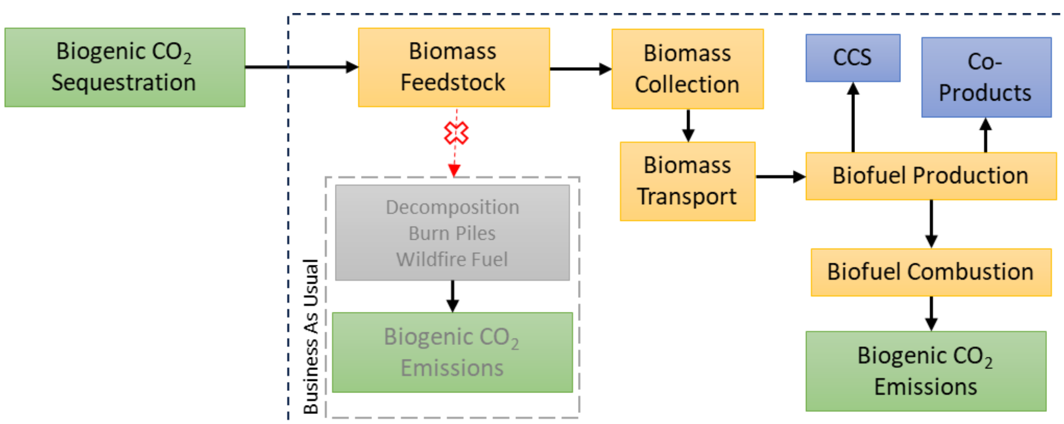

Figure 4. Example system boundary diagram for waste biomass to biofuel system.

An example net carbon balance of biomass-based fuels is illustrated in Figure 5. In this case, the growth of biomass results in the uptake of CO_2 from the atmosphere. The carbon is then the released as process emissions or carbon combusted in fuel. Carbon can also be stored either through CO_2 sequestration, biochar, or other means to result in a net sequestration (or carbon removal). Over a sufficiently long-time horizon, the growth and regrowth of crops over a range of harvest areas results in a net carbon neutral balance. Net increases or decreased in carbon storage depend on the details of the biomass harvesting system and alternative fate of the biomass feedstock, which are described in the following sections.

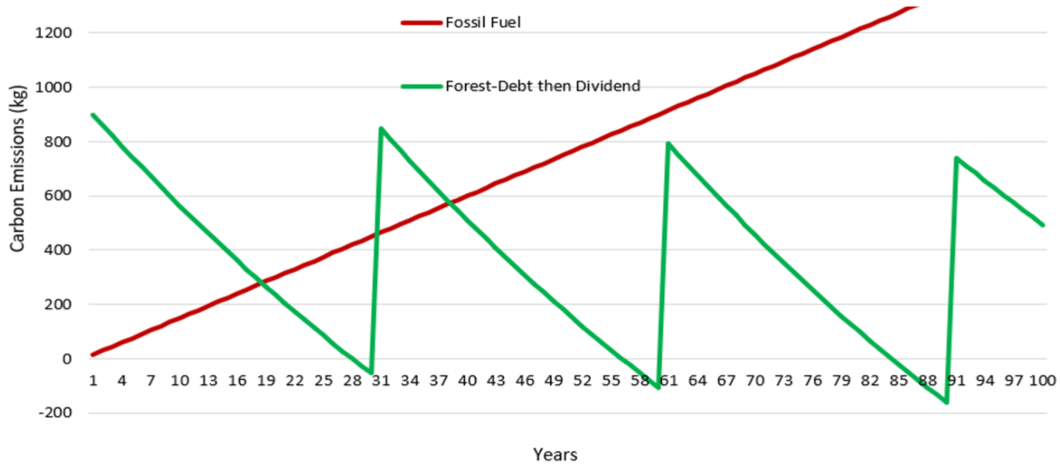

Figure 5. Example system boundary diagram for waste biomass to biofuel system.

Baseline Biomass Emissions & Alternative Fates

Net GHG emissions depends on a robust understanding of the baseline emissions of the biomass feedstock. These emissions will be dependent on the alternative fate of the biomass, that is, what would have happened to the biomass had the biomass not been converted to biofuel. Examples of alternative fates for a selection of possible waste biomass biofuel feedstocks are provided in Table 1.

Table 1. Example Alternative Fates for Select Feedstocks.

Feedstock	Example Alternative Fate
Forest pre-commercial thinnings[a]	Decomposition, burning, Collateral wildfire burning
Forest harvest residues (slash)	
Sawmill residues[b]	Decomposition, burning
Urban landscaping	Landfilling, evolving composting and treatment systems
Construction & Demolition	
Energy Crops	Required analysis of indirect effects

[a] Includes limbs, tree tops, and cull trees (those considered to be unsuitable for the production of lumber or other dry wood products due to either decay, form, limbiness, or splits). EPA's definition of thinnings under the RFS requires that biomass removal increases growth in adjacent trees.
[b] Includes bark, shavings, chips, unfinished wood cuts, and hog fuel.

This section examines options for assessing the alternative fate of biomass feedstocks. Biomass residues can have several fates, including decomposition, combustion, landfilling, or composting.

Avoided Combustion

Avoided combustion of biomass involves using waste biomass in a biofuel system instead of burning it directly. Combustion of biomass can occur for various reasons, including:

Agricultural burning: Farmers burn crop residues left in fields after harvest, as well as prunings from orchards and vineyards, to clear land, dispose of waste, and control weeds, diseases, and pests. In some cases, such as rice and pear cultivation, burning is the most efficient and effective method for disease control.

Forest residue burning: The U.S. Forest Service conducts controlled burns of piles of woody debris, commonly referred to as slash, to reduce hazardous fuels in forested areas. These piles are formed from the leftover woody materials following tree thinning or cutting activities.

When biomass is burned, all of the carbon that was sequestered in the biomass is released into the atmosphere over a short period of time. This can be modeled as a single time pulse. The biogenic carbon released during burning is equal to the biogenic carbon that would be released from the biofuel during vehicle combustion. Avoided burning does not necessarily correspond to a 1:1 relationship with biomass removal. Biomass may take several years to decompose. Alternatively controlled burning or wildfires could result in collateral fire damage with more forest material combusted than would otherwise be removed from thinning operations. With a 1:1 relationship between biomass alternatively burned or removed, the emissions from avoided burning and vehicle combustion cancel each other out, and the feedstock can be considered biogenic carbon neutral. Removal of residues with a requirement to increase surrounding tree growth also supports this 1:1 relationship.

In addition to avoiding the GHG emissions associated with the burning of biomass, converting biomass to biofuel avoids the release of air pollutants, such as particulate matter, nitrogen oxides, carbon monoxide, and sulfur dioxide.

COLLATERAL BURNING
Collateral burning refers to the unintentional combustion of wood waste, forest debris, or adjacent trees that remains within a forest ecosystem. When this organic material is left uncleared, it serves as additional fuel during wildfires or controlled burns. Consequently, the fires extend further and burn more intensely than they would have if the wood waste had been removed. This phenomenon contributes to elevated GHG emissions. Given the unpredictability of emissions resulting from collateral burning, which are influenced by variables like weather conditions, forest moisture content, and wind patterns, a conservative LCA approach would not count emissions associated with collateral burning for the purposes of biofuel CI calculations.

Avoided Decomposition

Biomass residues that are not intentionally burned may be left to decompose in place. In the absence of verifiable evidence that burning has been avoided, it is conservative to assume that the waste biomass would have been left to decompose. The following section will explore methods for verifying a feedstock's alternative fate.

During biomass decomposition in soil, some carbon becomes soil organic carbon (SOC), while the rest enters the atmosphere. A biofuel's greenhouse gas (GHG) impact depends on the balance between carbon sequestered as SOC and that released into the atmosphere. Decomposition rates and GHG balance are influenced by a variety of factors such as temperature, moisture, particle size, chemical conditions, and soil specific microbes, insect and plant species (Edmonds, 1991). To calculate the net GHG balance of avoided decomposition under the CA LCFS or similar regulatory frameworks, site-specific assumptions about decomposition rates and soil organic carbon (SOC) sequestration must be considered. The LCFS employs a GWP-100 for emission factors[2], meaning that any emissions or SOC sequestration within 100 years of biomass harvest should be incorporated into these assumptions.

[2] https://ww2.arb.ca.gov/ghg-gwps

Indirect Emission Considerations

The utilization of biomass for fuel production could result in an induced effect associated with the diversion of biomass resources from existing uses. This indirect land use conversion (iLUC) effect is part of the CI calculations of crop-based biofuels under the RFS and LCFS programs. Land use change can take two forms: direct and indirect. Direct land use change involves altering landscapes for biomass production, such as clearing forests for new biomass crops or switching from annual to perennial cropping systems. In contrast, indirect land use change occurs when biomass production indirectly affects other landscapes due to market-mediated effects. For example, higher prices might lead to forest clearance when food-producing land is redirected for biomass or carbon removal services. CARB has estimated indirect land use change for common biofuel crop feedstocks such as corn and soybean. ICAO has also examined iLUC emissions for a range of feedstocks including biomass energy crops and forest residues for aviation fuels under the CORSIA program (ICAO, 2021). The outcomes are particularly relevant for this study as forest residues are assigned an iLUC of 0 g CO_2e/MJ and farmed trees are assigned an iLUC of -5.2 to 8.6 g CO_2e/MJ.

Indirect emissions have also been examined by environmental groups. A study from ICCT assessed the risk of indirect impacts for a range of feedstocks for sustainable aviation fuels (Pavlenko, 2021). Feedstocks that have existing uses in industrial applications were ranked with a high risk of indirect effects. For example, animal tallow used as a renewable diesel feedstock might also be used as a feedstock for oleo chemicals or soap production. Waste resources such as sustainably harvested agricultural residues are likely to result in low indirect emissions as they do not have alternative economical uses. Table 2 provides an assessment of the indirect emission risks from various feedstocks. Biomass residues that do not have alternative markets fall into the low category. Feedstocks such as purpose grown biomass and agricultural commodities result in potential indirect effects due to the nature of economic markets. Indirect land use assessment performed for a range of biofuels used to produce sustainable aviation fuels (Prussi, et al., 2021) show very small indirect emission effects for sort rotation woody crops, which suggests a low displacement risk.

Table 2. Existing Markets, Substitute Materials, and Displacement Emission Risks for Feedstocks.

Feedstock	Existing Use	Likely Substitutes	Displacment Emissions Risk
Animal fats[a]	Oleo chemicals, boiler fuel	Fuel oil, vegetable oil	High
Corn oil[a]	Animal feed	Vegetable oil, corn, wheat, barley	High
Farmed trees[b]	Pulp and paper	Tree plantations	Medium
Molasses[a]	Animal feed	Grain, sugar beets	Medium
Renewable electricity[a]	Electricity sector	Marginal electricity	Medium
Forest residues[a]	Heat and power, soil health	Natural gas, grid electricity	Low[c]
Agricultural residues[a]	Livestock bedding and feed, mushroom cultivation, horticulture, heat and power, soil health	Cereals, lignocellulosic energy crops, renewable electricity, rubber, sand, gypsum, and dried manure	Low[c]
Urban landscaping[b]	Landfilling, composting, land spreading	Evolving composting and treatment systems	Low
Orchard prunings[b]	Heat and power, soil health	Natural gas, grid electricity	Low

[a] Rating from (Pavlenko, 2021)

[b] Assessment of risk is consistent with iLUC values assigned under CORSIA.

[c] For sustainably harvested removal rates.

[d] Alternative uses for these feedstocks are generally uneconomic due to transport costs and low value of end products.

RFS Compliant Biomass Feedstocks

Under the RFS, special consideration is given to fuels utilizing woody biomass as a feedstock. These considerations are meant to address the issues of alternative fate and indirect effects. The eligibility criteria for wood biomass under the Renewable Fuel Standard (RFS) are outlined in four key points[3:].

1. Woody biomass originating from federally owned land is deemed ineligible.
2. Woody biomass sourced from tree plantations, including planted trees, tree residue, slash, and pre-commercial thinnings are RFS compliant. However, on non-plantation land, only slash and pre-commercial thinnings meet the eligibility criteria.
3. to comply with RFS standards, tree plantations must have been cleared and actively managed before December 19, 2007.
4. Woody biomass derived from ecologically sensitive or old growth forests is explicitly excluded from eligibility under the non-ecologically sensitive criterion

The RFS further defines the following categories:

Planted Trees
Planted trees are defined as those harvested from a tree plantation, primarily consisting of hand- or machine-planted trees. It clarifies that trees naturally regenerated on plantation land also qualify. Naturally-regenerated trees on plantation land are permissible under the RFS program.

Tree Residue
Tree residue is defined as the wood residue generated from planted trees harvested in actively managed tree plantations. This residue, when processed for other applications like lumber, paper, or furniture, is considered eligible as renewable biomass. RINs can only be generated for the biogenic portion of tree residues.

Slash
Under the RFS, slash is defined as the material left on the forest floor after logging operations or disturbances like storms or fires. It includes tree tops, branches, bark, and unmerchantable trees. Slash must be from an eligible source to qualify as renewable biomass.

Pre-Commercial Thinnings
Pre-commercial thinnings involve removing trees to enhance the growth and quality of more desirable trees in a stand. The EPA does not limit the diameter of trees harvested during pre-commercial thinnings. However, trees that remain in a stand after the first thinning are restricted as qualified biomass.

Carbon Intensity Calculations

Calculating the net CO_2e emissions from a biomass to biofuel system includes the net carbon balance of the biomass material plus emissions associated with feedstock collection and processing. A baseline comparison of the GHG emissions from the biofuel project compared to the emissions from the alternative the biomass fate in the absence of the project would address the net carbon flux from the feedstock.

GHG Accounting Methods

Many LCA programs, models, and studies treat biogenic carbon in biomass from various sources as carbon-neutral. This carbon neutrality is implemented in different ways in GHG calculations (see

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[3] Environmental Protection Agency (EPA). (2010). Renewable Fuel Standard Program (RFS2). https://www.govinfo.gov/content/pkg/FR-2010-03-26/pdf/2010-3851.pdf

Table 3 for a selection of programs with citation). In corn ethanol pathways, for example, biogenic carbon is treated as neutral, with no carbon accounted for in either the tailpipe emissions nor the life cycle. In the case of forest residue to ethanol and biomass to power pathways, the GREET model accounts for the positive emissions from fuel combustion and the negative biogenic carbon uptake. This approach is sometimes referred to as Totality of Emissions accounting. Regardless of the accounting method, the biogenic uptake or avoided CO_2 from combustion balances the CO_2 in the end-use.

Upstream Life Cycle Emissions

The GHG footprint for various biomass feedstocks is shown in Figure 2. The GHG accounting system is based on the GREET model, which treats carbon in biomass as neutral as it is recently removed from the atmosphere[4]. The life cycle impacts are calculated in the model for forest residue as well as Life Cycle Associates' assessment of orchard prunings which are a proxy for forest waste which would have been alternatively burned. Avoided emissions from orchard prunings reflect additional impacts of burn piles. The avoided emissions reflect the impact of diverting biomass from burn treatments; however, regulators would need to authorize a credit even if the environmental benefits are readily apparent. The GHG footprint of various biomass feedstocks illustrates their range in GHG intensity and potential variability within the GREET modeling system.

Life Cycle GHG Emissions

Life cycle GHG emissions would include the full life cycle including feedstock collection, transport, fuel processing, CO_2 storage, fuel combustion and end use. For feedstocks with a net carbon neutral balance, the contribution to the life cycle includes feedstock emissions and any storage of CO_2. The contribution of feedstock production emissions from Figure 6 corresponds to the collection and processing emissions assigned to the fuel product such that:

$$E_{feed} = \text{Upstream feed (g GHG/ton)/yield (gal/ton)/LHV (MJ/gal)} \times \text{Loss Factor}$$

With an example of 35,000 g GHG/ton ÷ 50 gal/ton ÷ 126 MJ/gal × 1.0001 = 5.6 g CO_2e/MJ

These GHG emissions are allocated between multiple fuel products and the example here is a simple illustration of the feedstock contribution. This GHG intensity depends on the biomass yield and transport logistics.

[4] The GREET model is referenced in the Inflation Reduction Act as the basis for GHG emissions determination. CARB has not yet made a determination on the treatment of biogenic carbon neutral accounting as no projects using biomass feedstock have been completed.

Table 3. Carbon balance approach in select regulatory frameworks. This list provides example of biogenic carbon treatment for key programs and feedstock, but is not exhaustive.

Program	Approach	ILUC	Biomass Feedstock
EPA RFS (EPA, 2010)	Carbon Neutral	0	Forest Thinnings, Slash
EPA RFS (EPA, 2011)	Carbon Neutral	0	Corn stover
(EPA, 2022b)	Reports Biogenic Separately [a]	0	Biomass
CA LCFS Biomass Residue[b] (CARB, 2009a)	Carbon Neutral – positive emission with uptake credit	TBD	Forest Residue
CA LCFS Crop Residue[b] CARB 2015a, 2015b (CARB, 2014; CARB, 2009b)	Carbon Neutral	0	Corn Stover, Wheat Straw, Sugarcane Straw
CA LCFS CCS Protocol (CARB, 2018b)	Fully oxidized carbon in fuel or defer to CA-GREET	0	Wood and Wood Residuals
CA LCFS Grid Avg Power (CARB, 2018c)	Carbon Neutral – positive emission with uptake credit	0	NA
CA LCFS Biomass Energy Crop [b] (CARB, 2009a)	TBD	TBD	Farmed Trees
CA LCFS Crop-derived feedstock (CARB, 2023)	Carbon neutral with requirement to analyzed indirect emissions.	TBD	Biomass
CA RPS (CA PUC, 2009)	Carbon Neutral	0	Biomass
(ECCC, 2020)	Carbon Neutral	0	Biomass
EU REDII (EU, 2021)	Carbon Neutral	0	Biomass
(NZ ETS, 2021)	Carbon Neutral	0	Forest Biomass
(RTFO, 2021)	Carbon Neutral	0	Biomass
RenovaBio (RenovaBio, 2017)	Carbon Neutral	0	Biomass
CORSIA (Prussi, et al., 2021)	Carbon Neutral	0	Forest Residue
CORSIA (Prussi, et al., 2021)	Carbon Neutral	-5.2 g/MJ	Farmed Poplar

[a]Requires annual emissions for applicable categories to be reported separately for biogenic and non-biogenic.
[b]CA LCFS pathways were preliminary and never used for credit generation.
[c] Emission factors in the CCS protocol reflect fully oxidized carbon as CO_2 without reference to any biogenic uptake credit other than providing CA-GREET as an alternative source of emission factors.
[d]Canada CFS is in pre-publication.

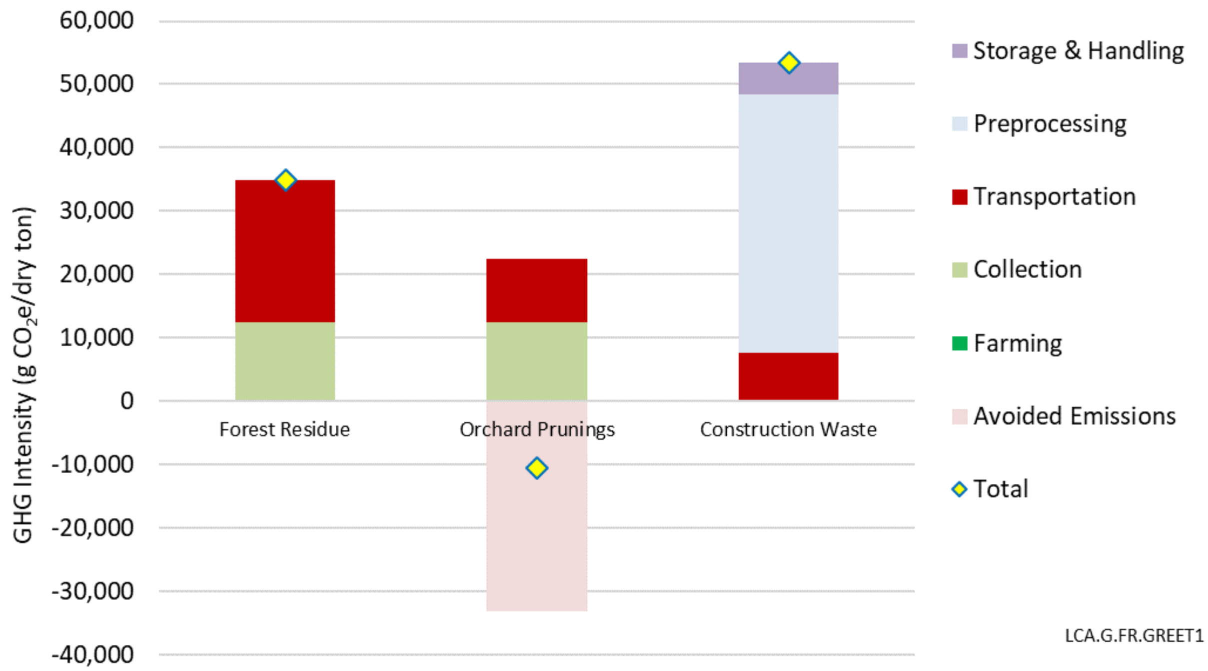

Figure 6. Life cycle GHG emissions for biomass materials from GREET model. Biogenic C neutral, no indirect effects

Verification Schemes for Biomass Residues

The use of waste biomass necessitates rigorous certification to ensure sustainability, responsible forest management, and wildfire mitigation. This section explores the certification options available under various forest management schemes, with a focus on Sustainable Forest Initiative (SFI), Forest Stewardship Council (FSC), and the Roundtable on Sustainable Biomaterials (RSB). It also discusses the relevance of other certification systems and initiatives in this context.

Certification Categories for Biomass Waste and Residues

The categories of solid biomass waste and residues include:

- Residues from Forestry and Agriculture: These originate directly from forests or agricultural activities, such as branch and top wood.
- Residues from Wood and Biomass Processing Activities: Generated during processing, these residues include sawdust, bark, and unusable wood parts. Other biomass residues may come from agri-food processing.
- Waste Wood: This refers to discarded wood products, which can be clean or contaminated (e.g., with paint).
- Other Organic Waste: Encompasses non-wood organic waste sources, such as household organics and grass cuttings from road maintenance.

Biomass Verification and Forest Management Options

To certify waste biomass as sustainable, fuel producers can use a variety of forest management verification schemes, such as the Sustainable Forestry Initiative (SFI), the Forest Stewardship Council (FSC), and the Roundtable on Sustainable Biomaterials (RSB). These programs are used internationally by a variety of stakeholders, including forest landowners, wood processors, and bioenergy producers, to demonstrate their commitment to sustainable forest management and meet the growing demand for sustainable wood products and bioenergy.

Specifically, SFI is used in the United States, Canada, and China to certify forest management and fiber sourcing practices. FSC is used in over 80 countries to certify forest management and chain of custody practices. RSB is used in over 30 countries to certify the sustainable production and use of biomass.

> **SFI** emphasizes standards, conservation, community, and education. It comprises 13 principles, 17 objectives, and additional performance metrics. SFI covers aspects such as forest management, fiber sourcing, and chain of custody. It promotes biodiversity conservation, environmental protection, and active community engagement.
>
> **FSC** is an international NGO committed to upholding sustainable forest management. It operates on 10 principles and 57 distinct criteria. FSC offers two primary certification types: forest management and chain of custody. These certifications aim to strike a balance between environmental, social, and economic aspects in forestry.
>
> **RSB** is a global initiative that promotes the sustainable production and use of biomass. It is guided by 12 well-defined principles that emphasize the environmental, social, and economic pillars of sustainability. Under RSB, forest residues must come from a sustainable forest management system (such as FSC or equivalent). RSB certification is one of the options for sustainable aviation fuels under CORSIA.

In addition to these forest management verification schemes, producers can also use other types of verification schemes, such as the International Sustainability and Carbon Certification (ISCC) and the USDA project for RFS biomass verification.

> **ISCC** is a universal certification system for sectors such as agriculture, forestry, and waste management. It offers two certification variants: ISCC EU, with meticulous audit standards, and ISCC DE, which underscores the traceability of waste and residues. ISCC is majorly focused on conservation of biodiversity, strict adherence to Good Agricultural and Environmental Condition (GAEC) standards, and a commitment to uphold labor rights. ISCC certification is one of the options for sustainable aviation fuels under CORSIA.

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High in the Sky with Low CI Hydrogen

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Synthetic paraffinic kerosene made from residues with solar power enables carbon-neutral flight.

Renewable fuels are gaining importance as an alternative source of liquid fuel due their renewability, chemical properties, and lower lifecycle emissions. The aviation industry's global greenhouse gas (GHG) emissions are 2.1% of the global share, and when non-carbon dioxide (CO_2) effects are included, it contributes approximately 4.9% to global warming (CAN, 2020). The international airline industry is committed to climate change goals which includes carbon neutral growth and cutting CO_2 emissions in half by 2050. Synthetic aviation fuels (SAF) are critical to achieve these targets. Hydrogen plays a role in the production of all aviation fuels and low carbon hydrogen can help expand SAF production.

Hydrogen and Jet Pathways

Six categories if SAF are approved as annexes to ASTM D7566. Four pathways with broad applicability are summarized below.

Annex A1 (Fischer-Tropsch FT-SPK is a mixture of iso- and n-alkanes derived from synthesis gas using the FT process. Syngas can be produced from reforming natural gas or from gasifying coal or biomass or the conversion of CO2 to CO with hydrogen. Synthetic fuel is a liquid fuel obtained from syngas, a blend of carbon monoxide (CO) and hydrogen, or carbon dioxide and hydrogen. Syngas is derived from gasification of solid feedstocks like coal or biomass, or by reforming natural gas. Carbon dioxide and green hydrogen are inputs to produce a carbon neutral synthetic fuel. Methods to refine synthetic fuels include Fischer-Tropsch conversion, pyrolysis, and hydrotreating of oils. Fischer Tropsch synthesis and power to fuel pathways involve the reaction of hydrogen with carbon monoxide to make fuel in the case of e-fuels all of the energy is derived from hydrogen. Hydrogen represents about 5% of the energy input for conventional FT and the hydrogen may be produced from the biomass syngas. The addition of supplemental hydrogen allows for the boosting of hydrogen fuel output.

Most synthetic fuels are created by mixing CO and hydrogen (syngas) and are produced through burning biomass and natural gas. Fischer-Tropsch (FT) synthesis is used to convert syngas into liquid hydrocarbon fuel. Fischer-Tropsch certified synthetic fuels are approved as 'drop-in' fuel, where the highest blend is a 50/50 blend of FT synthetic fuel and petroleum fuel.

Annex A2 (HEFA-SPK) consists of iso- and n-alkanes. The alkanes are the product of hydrotreating esters and fatty acids from fats, oils, and greases and from oilseed crops or algae. Most SAF produced today is derived from hydrotreating of oils and fats.

Annex A3 (SIP, hydroprocessed fermented sugar-synthetic iso-paraffins) is a single molecule, a 15-carbon hydrotreated sesquiterpene called farnesane, produced from fermentation of sugars such as sugarcane or corn dextrose. Sugar-based pathways will require somewhat larger amounts of hydrogen compared to HEFA due to the overall stoichiometry of the reaction

Annex A5 (alcohol-to-jet [ATJ]-SPK) is produced from ethanol or butanol. ATJ-SPK consists of iso-alkanes of 8, 12, or 16 carbons when starting from iso-butanol.

Hydrogen Boost

Various technologies use supplemental hydrogen sources as energy inputs and many such configurations are found in literature (Hillestad, 2018). The source of hydrogen affects the life cycle GHG emission and also improves renewable fuel production yield. Figure 1 shows a FT process that converts biomass to cellulosic biofuel using renewable hydrogen as an energy carrier. Biomass is converted to carbon monoxide, carbon dioxide, and hydrogen through gasification and gas conditioning. The same process configuration is adaptable to landfill gas feedstock. Carbon monoxide and hydrogen undergo FT synthesis upgrading, resulting in water as a byproduct. This water is sent through a solar powered electrolyzer to produce hydrogen. The hydrogen is then used in FT synthesis upgrading to produce low carbon cellulosic jet fuel via reaction with CO produced from gasification. With hydrogen production powered by wind and solar energy, lifecycle GHG emissions are over 90% lower than conventional fuels. Renewable hydrogen allows for the utilization of all of the carbon in the biomass. The Fischer-Tropsch process has been in use for over 60 years and has been approved as part of other RFS pathways.

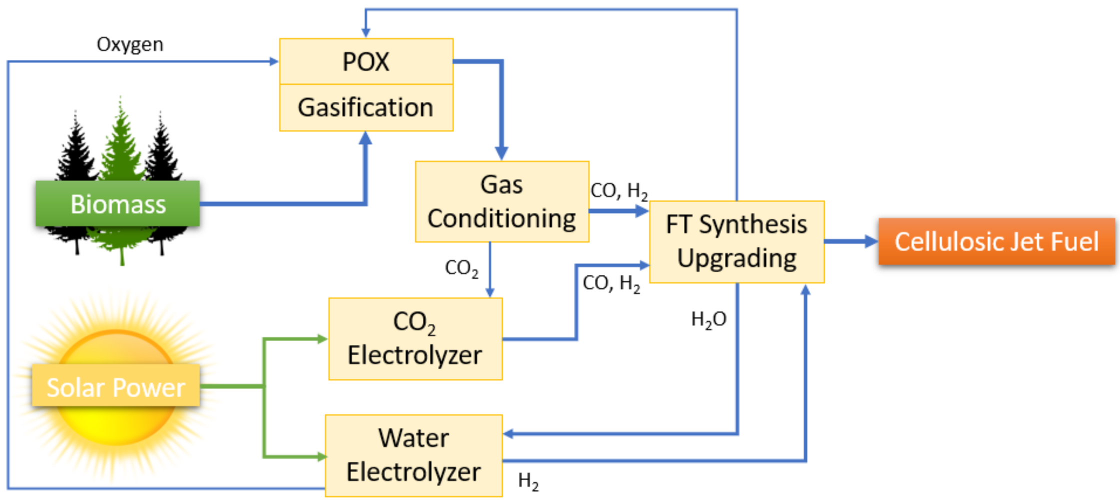

Figure 1. Renewable jet fuel production process from biomass and solar power. Blue lines indicate feedstock material flows while green lines indicate energy flows.

Policy Drivers

Numerous policy drivers provide an incentive for the use of low carbon hydrogen at both federal and state levels. Sources of low carbon hydrogen include electrolysis with renewable power or reforming of methane with low carbon sources of biogas as well as numerous other production methods. The role of low carbon hydrogen is either is enabled directly through the policy or helps with additional fuel volume and credit generation. The requirements for leading policies are briefly summarized.

EPA RFS - Renewable Fuel Standard

RFS requires renewable fuel production with categories for biomass to aviation fuel via Fischer Tropsch or pyrolysis for cellulosic fuels and hydrotreating of oils and fats for advanced biofuel. Ongoing evaluations will determine the role of hydrogen for new fuel pathways. (EPA, 2010; EPA, 2021). EPA is examining the effect of bonding carbon atoms obtained from biogenic carbon dioxide with hydrogen atoms obtained from fossil fuels. The RFS regulations at 40 CFR 80.1426(f)(4) determine the number of gallon-RINs generated for fuel that is produced by co-processing renewable biomass and non-renewable feedstocks simultaneously to produce a fuel. A concern for technologies using hydrogen power to convert biomass to biofuel is that the hydrogen used in processing would be considered a feedstock instead of an energy carrier. The distinction between a feedstock and an energy carrier is important; since hydrogen is not derived from biomass, it would not meet the requirements of a renewable feedstock under the RFS. If hydrogen were considered a feedstock, the resulting fuel would not be assigned the full value of its energy content under the RFS2. According to the regulation, RINs are assigned to the percentage of fuel that is derived from a renewable feedstock.

LCFS - Low Carbon Fuel Standards in California Oregon Washington and other states

LCFS regulations require the production of low carbon fuels with more credits generated for lower carbon intensity fuels. The use of supplemental low CI hydrogen would both increase fuel output and lower the carbon intensity of fuels.

CORSIA - Carbon Offsetting and Reduction Scheme for International Aviation

Airlines have committed to a 10% reduction in the carbon intensity of aviation fuels with an incentive to produce more SAF at a lower carbon intensity. CORSIA was approved in June 2018 that the international aviation sector is expected to collectively reduce its annual emissions by approximately 2,000 million tonnes of CO2 in 2050. The International Civil Aviation Organization (ICAO) anticipates in the early stages of CORSIA emission reduction goals will be met through carbon offsetting as the advanced alternative jet fuel industry develops. In later stages, emission reduction goals are expected to be met with alternative jet fuels and improved aircraft efficiency. By avoiding use of offsets, airline and environmental groups comply with

IRA - Inflation Reduction Act

Inflation reduction act provides for a producer tax credit for low carbon intensity hydrogen with the lowest threshold value at 0.45 kg CO_2e/kg hydrogen. Investment tax credits are also available for low carbon fuel production systems. The GREET model from Argonne National

Laboratory is required to assess the greenhouse gas (GHG) emissions from hydrogen production.

Low carbon hydrogen plays a critical role in aviation and the combination of policies leads further supports the role of low carbon hydrogen.

Emission Impacts

Various fuel pathways result in significant GHG reductions compared to petroleum jet as shown in Figure 2. Hydrogen is an integral part of all of the fuel production route. Boosting fuel output with FT fuels will reduce the carbon intensity (CI) but the more profound effect is the production of more fuel. E-fuels are an extreme example where all of the energy is derived from hydrogen. The CI values shown below are from the GREET model and the hydrogen boost cases represent the elimination of grid power and increase in yield from conventional FT pathways.

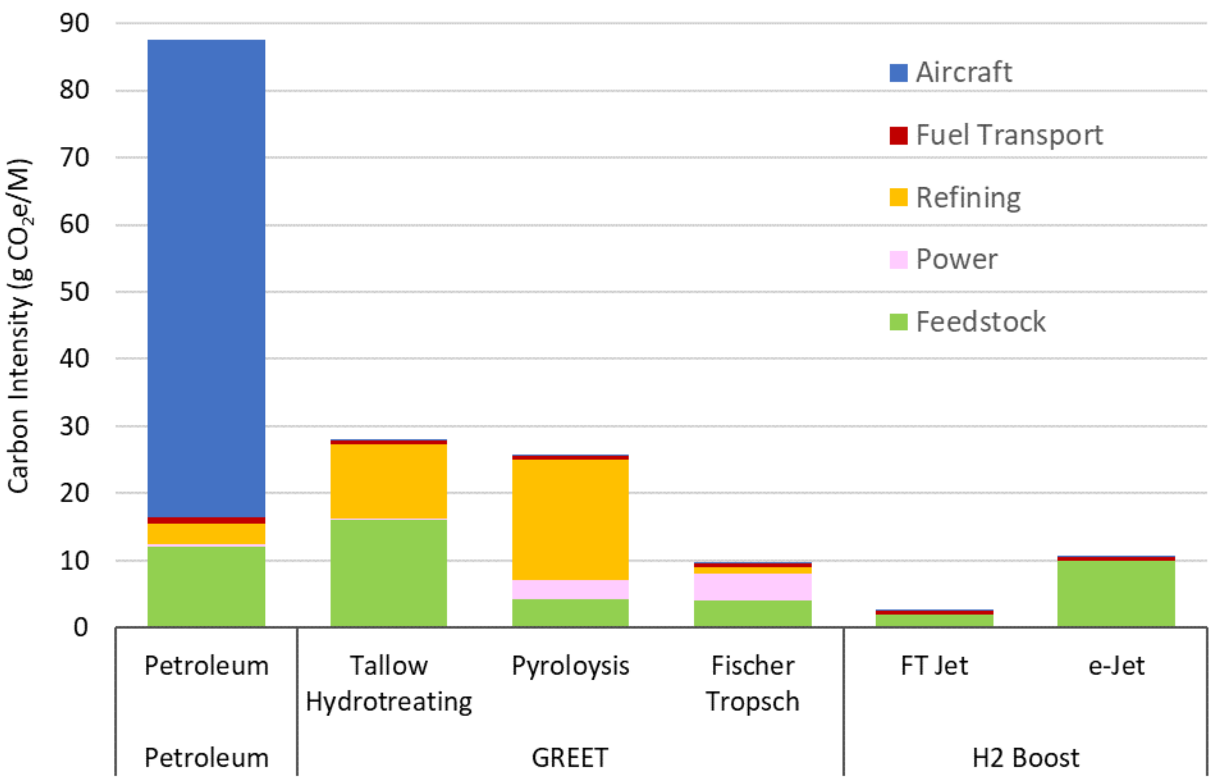

Figure 2. Renewable hydrogen lowers the GHG intensity of all jet fuel pathways.

The benefit of renewable hydrogen is reflected in the fraction of hydrogen that contributes to the total fuel product. In the case of hydrogen boosted fuels over 50% of the fuel energy is derived from hydrogen.

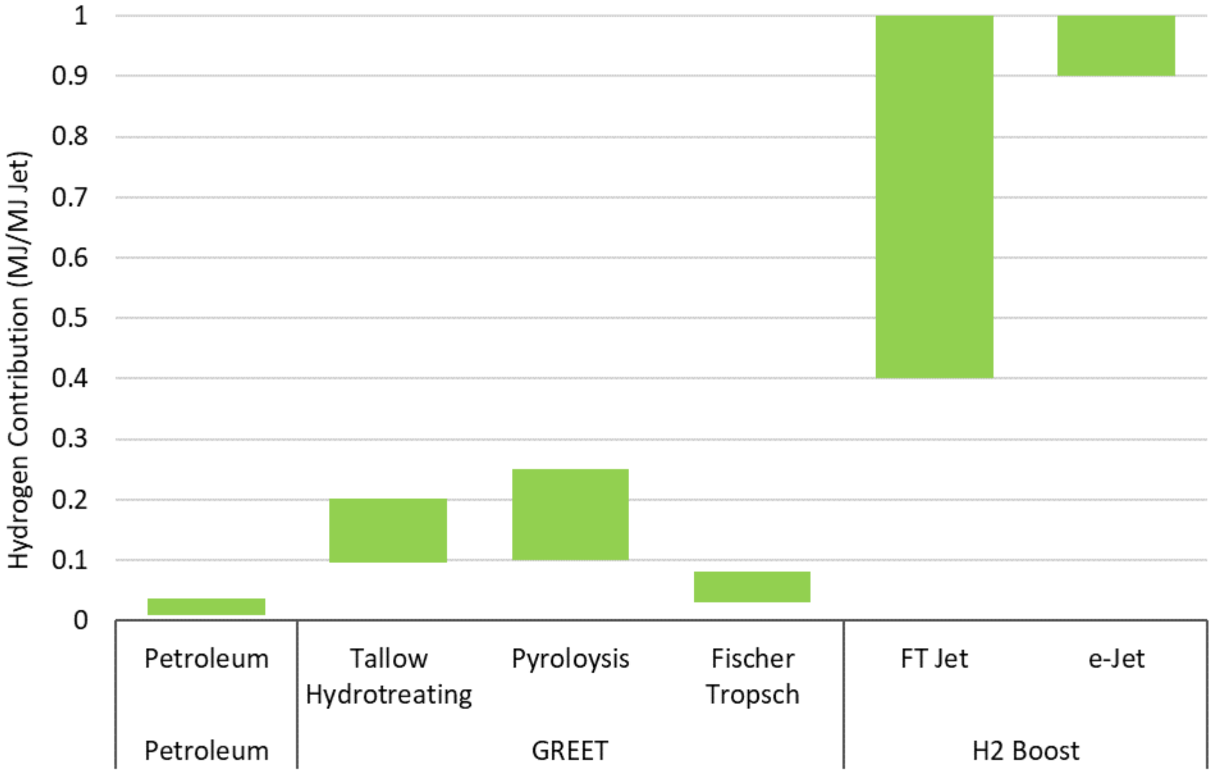

Figure 3. Renewable hydrogen can contribute to more jet fuel production by doubling the FT fuel output with full scale hydrogen boost. In the case of e-fuels, all of the energy is derived from hydrogen.

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